AMENDMENTS TO THE SPECIFICATION

Please delete paragraph 5, and amend paragraphs 4, 7, 8, 11, 12, 48, 49, 52, 59, 61, 65, 66, 67, 68, 80, 84, 85, 88, 90, 91, 92, and 109, as follows:

[0004] Transducers are widely used in measurement systems. The term transducer refers either to a sensor or an actuator. "Sensor" normally refers to a device that detects a change in a physical property due to a physical stimulus and turns that stimulus into a signal, which can be measured or recorded. "Actuator" refers to a device that accepts an input stimulus and converts it into a different kind of output stimulus. Then, the term "transducer" normally refers to a device that transfers energy of one kind to another in the same or a different form and includes either a "sensor" or an "actuator". ~~Thus the sensor is considered to be the sensing element itself and the transducer is considered to be the sensing element plus any associated circuitry for transmitting the measured physical change to a remote location. Transducers can be used to test the state of a mechanical or physical system or some portion of that system.~~

~~[0005] Through the use of transducers the properties of a system can be measured by observing the change in the properties of another system. For example, the absorption of ultraviolet light in some chemical compounds can be measured by directing a specific incident spectrum of~~

~~light onto a compound and measuring the intensity of reflected light as a function of wavelength. The sensor provides the measurement and the transducer converts it to an electrical signal that is representative of the measurement. From the signal a computer analyzes which wavelengths are absorbed and which are reflected while also taking into account any other factors.~~

[0007] There is a class of transducers that are called self-generating transducers, which include thermocouples, piezoelectric, and photovoltaic transducers among others. These transducers do not require a power supply because they generate a signal internally. A thermocouple, for example, produces a change in voltage in response to a temperature difference and a piezoelectric material generates a charge ~~that can be measured when it is stressed~~ in response to a mechanical stress. There are a number of piezoelectric devices including accelerometers.

[0008] Piezoelectric devices generally are particular types of crystals that develop a charge when stressed in a specific direction. The charge that develops in a piezoelectric transducer is proportional to both the piezoelectric constants of the material and the applied stress on the piezoelectric device. This piezoelectric constant depends on the mode of operation employed including bend, shear [[and]] or compression. Quartz crystals are used as piezoelectric devices in some systems, but

manufactured ceramics, such as Lead-zirconate-titanate (PZT) ceramics, are also widely used in piezoelectric transducers because they have a higher piezoelectric constant and therefore a higher charge output. Many piezoelectric transducers have built-in charge amplifiers. This greatly reduces problems with interference and low signal levels.

[0011] Accordingly, there is a need for improvement in the art to enable transducers to be tested in-situ and specifically, there is a need for an apparatus and method to allow in-situ testing of transducers such as piezoelectric transducers [[and]] <u>including</u> accelerometers that convert mechanical strain to an electric signal. There is a particular need for a self-testing transducer circuit. It is to such improvements that the present invention is directed.

[0012] The present invention is directed to an apparatus and method for ~~a measurement system for the~~ <u>an in-situ</u> testing of transducers, and more particularly ~~to the testing~~ of piezoelectric transducers. The measurement system includes a transducer <u>characterized by a natural resonant frequency</u>, a feedback amplifier coupled to the transducer and a signal processing circuit coupled to the output of the amplifier. The method of testing the transducer includes coupling the test signal to the transducer, disabling the amplifier, and measuring the response of the transducer to the test signal with the test processing circuit. The circuit itself used for performing this method

includes a piezoelectric transducer, an amplifier, including a feed-back circuit coupled to the amplifier for amplifying the output of the transducer, a power source coupled to the amplifier, [[a]] the signal source coupled to the transducer, generating a test signal having a frequency spectrum at least overlapping the [[self]] natural resonant frequency of ~~the transducer coupled to~~ the transducer, and a switch coupled to the amplifier capable of disabling the amplifier.

[0048] The transducer 12 of this invention can include one or more of a piezoelectric, capacitive or inductive devices, and can be from a class of transducers that are called self-generating transducers ~~which include thermal couples, piezoelectric, and photovoltaic transducers among others~~. The present invention is well suited for application with a piezoelectric accelerometer ~~that can measure mass compression or displacement and generate a measurable charge~~. The self-generating transducers do not require an external power supply because they generate a signal internally. Piezoelectric transducers have one or more characteristic resonant frequencies. The piezoelectric accelerometers can be crystals such as quartz crystals or ceramics such as Lead-Zirconate-Titanate (PZT). It is possible to send signals near the resonant frequencies to the transducer and measure the output in that frequency band without interfering with the operation of the transducer.

[0049] As shown in Figure 1, the self-testing transducer circuit 10 includes the transducer 12, which is characterized by a [[self-]] natural resonant frequency natural resonant frequency, the amplifier 14 connected to the transducer that amplifies a transducer output signal 33, the signal generator 18 that generates the test signal 20 that has a spectrum at least overlapping the [[self-]] natural resonant frequency of the transducer also connected to the amplifier, and the analyzer 21 including the microcomputer 26. The analyzer 21 is connected to the output of the amplifier 16 for measuring the response of the transducer to the test signal 20 and to characterize at least one parameter of the transducer 12 such as mechanical quality factor Q, the resonant frequency, the total impedance, Zt, and the mechanical impedance, Zm.

[0052] As shown in Figure 2 the self-testing transducer circuit 10 includes the transducer 12, which is characterized by a [[self-]] natural resonant frequency natural resonant frequency. The amplifier, often called a preamplifier 14 is connected to the transducer and the self-testing transducer circuit 10 includes a feedback impedance loop 34 with impedance (Z_f) 36. The self-testing transducer circuit 10 shown also includes the signal generator 18 to generate the test signal 20 connected to the preamplifier 14 along with a reference 38, shown here as a reference voltage source 38. The preamplifier output 40 is connected to various analyzers, such as analyzer 21 shown in Figure 1. The analyzer

measures the response of the transducer to the test signal and thus characterizes at least one parameter of the transducer.

[0056] Of interest in the present application is the apparent admittance (or equivalently the impedance) at the output of the sensor. This may be calculated in the following manner.

$$\begin{pmatrix} f \\ v \end{pmatrix} = \begin{pmatrix} 1 & Z_m \\ 0 & 1 \end{pmatrix} \begin{pmatrix} S & 0 \\ 0 & -1/S \end{pmatrix} \begin{pmatrix} 1 & 0 \\ -Y_e & 1 \end{pmatrix} \begin{pmatrix} e \\ i \end{pmatrix} = \begin{pmatrix} S + \frac{Z_m Y_e}{S} & -\frac{Z_m}{S} \\ \frac{Y_e}{S} & -\frac{1}{S} \end{pmatrix} \begin{pmatrix} e \\ i \end{pmatrix} \qquad (2)$$

First, we multiply the three central matrices displayed in Figure 3 to find the system of equations that relate the input force and velocity *(f,v)* to the output voltage and current *(e,i)* as shown above in Equation (2).

[0057] Next we assume that the input force is zero, i.e., no external signals are applied to the accelerometer. Solving the first of the two ~~equations~~ represented in ~~Equation.~~ <u>Equation</u> (2) for *i/e*, the total output admittance of the sensor, $Y_{e\ total}$, is found.

[0059] The first two embodiments of the self-test apparatus and method of this invention are based on a generic operational amplifier as shown by (14) in Figure 2. The third embodiment uses a "two-wire" charge preamplifier widely used with piezoelectric accelerometers. These self-test apparatus and procedures are for a transducer self-test circuit 10 to determine if a major failure, performance degradation or change in calibration of the sensor has occurred. The present invention also has the

ability to track ~~the calibration~~ sensitivity of an initially calibrated sensor ~~may be sufficient to insure sensor data integrity~~ by tracking changes in calibration from an initial primary calibration.

[0061] A voltage mode self-test circuit 64 is shown in Figure 5. A transducer 66 is represented by an electrical impedance 68 and signal generator 70 that is connected to the non-inverting input of an operational amplifier 72.

$$v_{out} = \left(\frac{Z_1 + Z_f}{Z_1}\right)\left(\frac{1}{1+\left(Z_{e\,total}/R_r\right)\left(1+j\omega R_r C_c\right)}\right)\left(j\omega C_c Z_{e\,total} v_c + \frac{Z_t}{R_r} V_r + v_s\right) \quad \cancel{[[(4)]]}$$

[0065] The self-test feature is implemented by a voltage source 136, v_c, coupled to the input of the charge preamplifier through a capacitor 138, C_c. Retrofitting a conventional sensor of the "two wire" charge preamplifier" type to the self-test capable sensor circuit 110 requires adding the self-test signal source 136, the coupling capacitor 138, and adapting the software to run a testing sequence. The two-wire self-test circuit was analyzed using the ~~pspice~~ Pspice circuit simulation described below. Included are sample computed output spectra for representative sensor and test circuit parameters. The sample computations are summarized below.

[0066] In practice the self-test voltage source will be either broadband pseudo-random white noise or a swept sine wave. Assuming that v_c is broad band white noise the output spectra for the three-wire

self-test configurations may be computed from ~~Equations 4 and 5~~ Equation 3. Listed below are parameters representative of the OST charge mode accelerometers will be used in the sample computations. The relevant sensor parameters are given in Table 1. The electromechanical coupling constant S (C/m), coulomb per meter, may be computed from the accelerometer sensitivity (pC/g) by multiplying the sensitivity by $[10^{-12}\ (2Bf_0)^2/9.8)$.

OST Model Number	A5006	A5013	A8120
Sensitivity pc/g)	5	12	120
Mounted frequency f_0	35	30	20
Proof Mass (m_p) (gm)	0.7	1.6	17
"S" (C/m)	0.025	0.044	0.19
Capacitance (pF)	400	400	3600
Total Mass (m_T) (gm)	2.2	3.0	25

Table 1 Parameters of OST charge-mode accelerometers

[0067] The accelerometer is represented mechanically by a simple harmonic oscillator with mass m, resonant frequency f_0 and mechanical quality factor Q. The mechanical impedance, Z_m is the ratio of the force to the velocity of the oscillator, which in the frequency domain is given by equation [[(6)]] (3) below:

$$Z_m(\omega) = \frac{m}{j\omega}\left(\omega\frac{2}{0} - \omega^2 + \frac{j\omega\omega_0}{Q}\right) \quad \text{where } \omega_0 = 2\pi f_0. \qquad [[(6)]]\ \ (3)$$

[0068] In the first example shown, Fig 8, the computed three-wire voltage mode self-test output from the self-test circuit 64 is shown for the A5006 model accelerometer. The self-test circuit parameter values are displayed on the graph 140. The feedback capacitance and the capacitance at the inverting amplifier input are chosen to have the same value as the accelerometer, which gives a signal gain of 2 according to Equation [[4]] 3. Figure 8 shows the representative output spectrum for the voltage-mode self-test circuit 64.

[0080] The self-test circuits presented in this ~~report~~ disclosure permit the user to determine the "health" of a piezoelectric acceleration sensor, including the preamplifier, by measuring the frequency response of the sensor-circuit combination. This is accomplished by coupling a broadband noise or swept sine wave source to the input of a self-test circuit. The frequency response of the circuit yields a measure of the accelerometer's output impedance, which is a function of its mechanical parameters, electrical parameters, piezoelectric coupling strength and mounting conditions. Electrical parameters of the preamplifier also may be inferred from the frequency response data.

[0084] In self-test mode a test signal is applied through a capacitor in 204, such as a small value capacitor, to the circuit node 206 between the piezoelectric transducer 202 and the amplifier 14 as shown in Figure 16. The capacitor can actually be any element that supplies an

impedance between the signal source and the amplifier. In the self-test mode with a test signal switch 207, and a power supply 208 connected to the amplifier 14, the ~~amplified~~ amplifier can be turned off or disabled with the aid of the test signal switch. Disabling the amplifier can be accomplished in a number of ways with a switch including placing the test signal switch [[207]] 207a between the power source and the amplifier as shown in Figure 17 or switch 207b alternatively between the signal source and the transducer so that the amplifier is always off when a test is made as shown in Figure 18. The amplifier can also be disabled or "turned off" a number of other ways that prevent the amplifier from being an effective part of the circuit and thus prevents noise from the circuit interfering with the analysis of the piezoelectric transducer output. Some of these will be discussed in detail in the following discussion.

[0085] As shown in Figure 15, the [[The]] self-test signal output goes through the amplifier feedback circuit (stand alone or internal) indicated by line 209, to the analog to digital converter (A/D) 22 and then to the digital signal processor 24. Test-signals such as a pseudorandom noise, a periodic chirp or a swept narrow band signal can be used. The processor 24 analyzes the test-signal and provides signal which goes through the digital analog converter 32 and capacitor 204 to circuit node 206.

[0088] During the self-test method of the present invention, the amplifier is turned off. This substantially decreases noise from the transducer 202 output measurement signal (e.g., vibration). This decrease in noise helps accomplish a better testing method as described below. Figure 19B shows a self-test response signal when the amplifier is turned off, the test signal is very clean. During the self-test method of this invention, as shown in Figures 15 - 19, the amplitude level of the self-test signal at node 206 must be maximized to the maximum allowed by the transducer and amplifier circuits. For example, if during self-test there is a high level of vibration and the self-test input signals equals 500 mV [[(f_{mix})]], the self-test response signal is noisy as shown in Figure 20A. The noise substantially decreases when the self-test signal amplitude is increased, equal to 5 V as shown on Figure 20B. It is important to maximize ~~f_{test} to all but saturate~~ the self-test signal amplitude but avoiding the circuit saturating for best results.

[0090] The self-test method of this invention consists of two phases:

PHASE 1: Initial transducer signature measurement is determined during an initial transducer installation (mounting) on object. This signature is the frequency and amplitude of peaks (see the spectrum response shown on 21A for an example of this response). The signature is measured twice:

-The signature (frequency f_{sun} and amplitude A_{sun}) of the unmounted transducer. It is measured before the transducer is mounted on an object. Usually the frequency f_{sun} is close to the transducer natural resonance frequency.

-The signature (frequency *[[f sun]]* $\underline{f_{sm}}$ and amplitude *[[A sun]]* $A_{\underline{sm}}$) of the mounted transducer. It is measured after the transducer is installed or mounted on an object. Usually the frequency *[[f sun]]* $\underline{f_{sm}}$ is close to mounted resonance frequency of the transducer. All signature data are recorded in memory.

PHASE 2: Recurring in-situ self-test measurements can be made by measuring the frequency and amplitude (f_t *and* A_t) of one or more peaks and comparing these with transducer signature data (f_{sun}, A_{sun}, f_{sm}, A_{sm}).

[0091] A self-test in-situ method for use with a piezoelectric transducer circuit including an amplifier. The method including a measurement mode (of sensor) when the amplifier is on and a self test mode when the amplifier is off to reduce inherent noise in conjunction with an established baseline standard by; including the following steps:

1. Measurement of the output parameter (such as amplitude) of a piezoelectric transducer in response to application of an input testing amplitude (voltage) with frequency range overlapping the natural resonant frequency of the piezoelectric transducer before mounting in

the measurement situation (such as having the piezoelectric transducer mounted on an object).

2. Measurement of the output parameters (such as amplitude) of a piezoelectric transducer in response to application of an input testing amplitude (voltage) with frequency range overlapping the resonant frequency of the piezoelectric transducer after mounting in the measurement situation.

3. Establish a ratio of output/input parameters (such as the amplitudes) over test frequency range to establish a standard spectra in mounted and unmounted situations ("ratio spectra" mounted/ unmounted).

4. Recurring in-situ self test measurements (ie periodically and/or as needed, for instance when a problem arises] of in-situ output/input parameters (such as amplitudes) to create "ratio spectra".

5. In these recurring in-situ circumstances (ie periodically and/or when a problem arises) use the measured in-situ output/input parameters (such as amplitudes) and created "ratio spectra" to compare to the standard output/input standard "ratio spectra" for mounted and unmounted situations to determine if there have been changes to the sensor, including those discussed below during operations. This can be done with plots, calculations or a combination of these. These tests may be digitized and/or programmed into the software or hardware.

[0092] Referring to FIG. 21A (mounted) and FIG. 21B (unmounted), the following steps help clarify the present invention:

STEP ONE OF SIGNATURE STANDARD (FIG. [[19B]] 21A) Before mounting piezoelectric transducer:

Unmounted peak frequency f_{sun} - frequency signature of an unmounted transducer. Unmounted-peak amplitude A_{sun} - amplitude signature of an unmounted transducer.

STEP TWO OF ~~SUGNATURE~~ SIGNATURE STANDARD (FIG. [[19A]] 21B) - After mounting piezoelectric transducer:

Mounted peak frequency f_{sm} - frequency signature of mounted transducer.

Mounted peak amplitude A_{sm} - amplitude signature of mounted transducer.

STEP THREE - when in self test mode:

In-situ peak frequency f_t - peak frequency during self-test.
In-situ peak amplitude A_t - amplitude during self-test.

So, when the mounted/unmounted ratio spectra are used separately or preferably superimposed, they can determine one of the following:

1. If $f_t \approx f_{sm}$ and $A_t \approx A_{sm}$ then the piezoelectric transducer is mounted properly and works well (sensitivity unchanged).

2. If $f_t \approx f_{sm}$ <u>and $A_t \neq A_{sm}$</u> but then the piezoelectric transducer is <u>properly</u> mounted but its sensitivity has dropped due to transducer failure or environmental influence.

NOTE that a change in temperature [[would]] <u>may</u> create changes in sensitivity so it is important to have environmentally normalized signatures.

3. If $f_t \approx f_{sun}$ then the piezoelectric transducer is not mounted properly or may fall off.

4. If $f_t \neq f_{sun}$ and $f_t \neq f_{sm}$ then the piezoelectric transducer is poorly mounted or compromised.

[00109] The vast majority of sensors currently manufactured and deployed are still single analog signal output devices. The systems that use these sensors can only recognize the intended analog signal. Therefore, what is needed is a design of a conventional transducer with self-test and a method for communicating the results to the outside world. The inventors have discovered the following unique approaches to this challenge:

1. An analog output transducer with built-in test whose output is programmed to assume a predetermined value when an

unacceptable fault condition is detected. (Preferred embodiment: [[A]] a 4 - 20 mA transmitter may be programmed to provide a constant output such as 4 or 20 mA upon fault detection. Or, in order to more conclusively identify that the output is due to self-test results, the transducer may be programmed to alternate values in a predetermined pattern such as alternating once per second between one of the extreme values 4 or 20 mA and the current output of the transducer. The same could apply to analog voltage or frequency output transducers.)

2. An analog output transducer with built-in test whose output is modulated with a signal reflecting the results of a detected fault condition. (Preferred embodiment: [[A]] a 4 - 20 mA transmitter may have a method by which its output signal or power line may be modulated by a signal to initiate and communicated the status of an internal self-test function. This requires the addition of an interface at the signal's receiving and compatible with this communication method. The modulated signal my be voltage or current bias, a fixed or varying frequency, or a modulated pulse train.

3. An analog output transducer with built-in test that provides an additional interface for communication of test results.

(Preferred embodiment: a 4 - 20 mA transmitter may include an LCD and key pad interface that can be used to initiate and communicate the results of testing in digital or human readable form. Alternatively, the additional interface might be connector or wireless interface that uses a digital communication protocol.)

4. An analog output transducer with built-in test that uses the results or the test to appropriately compensate its analog output signal. (Preferred embodiment: ~~A 4 - 200 mA~~ a 4 - 20 mA transmitter may include a compensation algorithm to the sensor output when self-test indicates a fault condition. An example would be to multiply the analog output sensor signal by 1.05 when a 5% reduction in sensitivity is detected. This method may be used in combination with the previous claims when a fault condition or severity is detected that an internal algorithm can no longer adequately compensate.)